Channel Sounding Techniques for Applications in THz Communications

A first correlation based channel sounder for ultra-wideband dynamic channel measurements at 300 GHz

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Abstract—**THz communications are a promising possibility to achieve data rates around and above 100 Gbit/s in the near future. Nevertheless, for every communication system the knowledge of the typical propagation characteristics is essential for each application scenario. In this paper, currently available channel sounding techniques are briefly reviewed in regard to the proposed applications for THz communications. Finally, a novel correlation-based channel sounder for 300 GHz is presented and evaluated according to the applications scenarios.**

Keywords— Submillimeter wave propagation; MIMO; Submillimeter wave measurements; radio propagation; THz communications;

I. Introduction

The ever increasing demand for higher data rates of 100 Gbit/s in the near future [1] can be satisfied by three means or combinations of these: increasing the spectral efficiency, exploiting multipath propagation or increasing the bandwidth. With state-of-the-art forward error correction codes, the spectral efficiency is already very close to the Shannon limit. Therefore, (massive) MIMO is one intensively studied possibility for further improvements at the cost of quite complex channel estimation techniques. Another obvious approach is to increase the channel bandwidth. However, below 275 GHz a significant increase of bandwidth might be impossible because all frequencies are already used with only regional white spaces remaining. Beyond 275 GHz and up to 3 THz there are no active services, yet. Bandwidths of 50 GHz can be realized in this frequency range if the challenges in technology and propagation conditions are mastered.

The propagation at 300 GHz can be characterized as quasi optical with distinctive propagation paths between transmitter and receiver. A very high free space path loss of approximately 100 dB for 10 m at 300 GHz in combination with limited output powers of below 0 dBm require the use of directive antennas [2]. From the technology point of view, the limited output power is a challenge. In addition, mostly simple modulation schemes, like QPSK, are proposed since phase noise is limiting the achievable modulation order. An example for an electronic approach can be found in [3].

Anyway, the technology has reached a level of maturity, so that within the Project IEEE P802.15.3d a first standard for transmission links at 300 GHz has been developed and published. [4, 5]

An overview of the near future applications considered in this new standard combined with an outlook to the further foreseeable future is presented in section II. Based on these applications, reasonable (minimal) requirements for channel measurements are derived as well. In section III, a brief overview of the most important channel measurement techniques for THz communications is presented. Finally, a novel and - to the best of the author's knowledge - the only available 300 GHz correlation based ultra-wideband channel sounder is presented.

II. Applications and Requirements

For every future communication system, the targeted applications introduce a set of requirements and constraints for meaningful propagation measurements. Consequently, the applications for THz communications are briefly presented first. The focus is always on important facts for measurements. A baseline of useful requirements for measurement equipment is then derived under the assumption that one measurement device can be used in the measurements for all or most applications.

A. Applications for THz Communications

A glance at the scope of the new standard [6] reveals that all considered applications are limited to point-to-point setups in rather static environments. Namely, intra device, close proximity, additional wireless links in data centers and wireless back- and fronthaul links for mobile cellular networks are identified. Except for the last one, they all have in common to be indoor with transmitting distances between one centimeter and some few ten meters. Link distances for front- and backhauls are between 50 to 300 m. The increasing free space path loss for longer distances is addressed by antenna gains increasing from a few Decibels to 50 dBi (parabolic dish antennas). With the short wave lengths, antennas can be realized inside an IC housing or even be integrated on the die.

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For the modulation schemes, On-Off Keying and BPSK to 16 QAM are defined. Still, the lower order schemes are required in the baseline and more likely to be implemented in early products. Thus, wide bandwidths are necessary.

More future looking applications [7] advance from e.g. a wireless link between a laptop and an external hard drive to a fully-fledged WiFi scenario or the access link in a cellular network. For these applications transmitter and receiver do not a priori know each other's position. Consequently, beam steering and algorithms for device discovery are required. Furthermore, portable and mobile devices introduce dynamic scenarios, especially with moving objects which can interfere with the transmission. Also the transmitter or the receiver may be moving. Hence, tracking of the devices is of interest as well. Simple MIMO techniques could be used for this whereas distributed MIMO approaches may provide wider coverage.

B. Requirements for THz Channel Measurements

In each of the following subsections a figure of merit is discussed. For the very broad range of applications, it is obviously not possible to present exact minimum and/or maximum values for each one. Nevertheless, numbers are given combined with some reasoning to provide orientation and to assess channel sounding techniques.

Mobility is, at least for the future applications, a key challenge. Thus, the terminology according to Bello [8] is used: The time-variant channel impulse response $h(t, \tau)$ depends on the delay and the time. The delay is characterizing the time within an impulse response while time is the global time.

1) Bandwidth

The minimal bandwidth supported by the upcoming IEEE standard is 2.16 GHz for compatibility reasons. For meaningful data transmissions an absolute minimum of 4.32 GHz will be required. Typically, the envisioned bandwidth will be several tens of gigahertz. For instance 100 Gbit/s can be achieved with a QPSK modulation with a bandwidth of approximately 50 GHz, or an 8 PSK with approx. 33 GHz, ...

2) Antenna directivity

Clearly, omnidirectional antennas are not sufficient for two reasons: First, most applications will use directive antennas to cope with the free space loss. Measurements with omnidirectional antennas do not include any spatial information about the propagation paths. This way the measurements could not be used to predict the actual scenario. Second, also in the measurements, the free space path loss will require directive antennas for sufficient received power and dynamic range. For these reasons, a measurement should be done with directive antennas which can be rotated to record the spatially dependent conditions. Consequently, the question is more about finding an optimum between acquisition speed, spatial resolution of propagation paths and enough received power. For a good coverage of the applications a measurement device should have exchangeable antennas.

3) Measurement Distance

With the outdoor applications, the length of the direct path between the transmitter and the receiver is in the range of a few centimeters to 300 m. Even for indoor applications, where this path length is only about e.g. 10 m, the measurable path length should be significantly longer. For instance, a distance of 100 m allows for propagation paths with higher order reflections. At the same time, the minimal separable distance for two propagation paths should be in the range of centimeters.

4) Dynamic Range

The dynamic range is the range between the strongest possible received signal and the noise floor. Thus, it mainly influences the maximum detectable path loss originating from e.g. the path length and the order of reflection. According to [9] a dynamic range of approx. 40 dB is enough to see 3rd order reflections in a small office at 300 GHz. However, the dynamic range of a measurement device should exceed this. Otherwise it would be important that the strongest received signal matches the upper limited of the dynamic range.

5) Doppler Frequency

The Doppler frequency depends on the speed and direction of moving objects. For THz communications, it stands to reason that walking persons have to be taken into account in the measurements. A person can e.g. cross through a transmission path, be a scatter in the vicinity of the link or carry either the transmitter or the receiver. The maximum Doppler frequency $f_{\mathrm{d,max}}$ depends on the maximum speed v and the wave length λ. [10]

$$f_{\mathrm{d,max}} = v / \lambda \tag{1}$$

The maximum speed of a pedestrian is assumed to be 5 km/h. With a wave length of ~1 mm (300 GHz) the maximum Doppler frequency is 1.4 kHz. Analogous to the Nyquist-Shannon sampling theorem, channel impulse responses - as a whole - have to be recorded with a rate of at least twice the maximum Doppler frequency to avoid aliasing effects e.g. in the Doppler-variant impulse response [8]. Anyway, it's noteworthy that the arms of a person move faster, so that even for a pedestrian higher Doppler frequencies occur.

6) Other requirements

A channel sounder for THz communications has to be portable for practical measurements in different scenarios. MIMO measurements are beneficial to estimate the position of another device. Distributed MIMO could be used to achieve an increased coverage area or to investigate the interference from adjacent links.

III. Review of THz Channel Sounding Techniques

There are three main techniques for the estimation of terrestrial propagation characteristics in the THz range, namely, THz Time Domain Spectroscopy (TDS), Vector Network Analyzer (VNA) measurements and Correlation based Sounding (CS). In addition there are reported experiments with signal generators and signal analyzers. Essentially, these are rather similar to VNA measurements with less precision and thus not discussed separately here. Each technique is briefly

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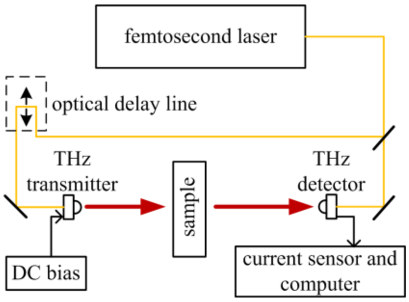

Fig. 1 Transmission type spectrometer (according to [11])

reviewed in this section with a focus to the individual strengths and weaknesses in face of the previously introduced applications. A fundamental requirement for all these techniques is the quasi-stationarity of the channel during the acquisition of one impulse response.

A. THz Time Domain Spectroscopy

A detailed description of THz Time Domain Spectroscopy can be found in [11] and it is summarized here for the sake of a complete picture. In principle the light of an ultrashort pulsed laser is send to a transmitter which converts this pulse to one in the THz range, c.f. Fig. 1. The receiver consists of a detector which transforms the received field strength of the THz impulse into an electrical signal when an optical impulse hits this detector. The optical impulse is generated by the same ultrashort pulsed laser as used for the transmitter. By introducing an optical delay line, the channel impulse response can be sampled.

The advantage of THz TDS is that a huge bandwidth, e.g. 100 GHz to 10 THz, can be covered by one setup due to the short pulses. The dynamic range easily exceeds 60 dB. Since a spectrometer is quite large (optical bench) and has a very limited output power, it is not suitable to measure the propagation conditions in any large scenario (data center, office …). Nevertheless, it is excellent for estimating electrical and scattering parameters of material samples.

B. Vector Network Measurements

The principle of operation of a two-port VNA is well known, e.g. [12], and can be summarized as follows: On the first port a sinusoid signal is transmitted. After a short time, ideally when a steady state is reached, the received complex amplitude of the transmitted signal is measured at port one and at port two. The scattering parameters S_{11} and S_{21} are then derived by normalizing the received signals to the transmitted one. A wide bandwidth can be sampled by stepping through several frequencies with a selectable increment. Analogous, S_{22} and S_{12} can be measured when port two is the transmitting one.

For THz communications, most manufactures use frequency extensions with four-port VNAs [13,14]. The additional two ports only generate a local oscillator for the mixer in the extensions. These frequency extensions are equipped with waveguide flanges for the bands up to 1.5 THz. Thus, the Channel Transfer Function (CTF) of a radio link can be sampled as S_{21} (or S_{12}) within one waveguide band at a time, e.g. 220 to 325 GHz. The resolution in the frequency domain can easily be chosen in combination with the start/stop frequency and the number of steps. A dynamic range of 60 dB and more can be realized by adjusting the measurement bandwidth towards smaller values. On the downside increasing the bandwidth or the frequency resolution or decreasing the measurement bandwidth leads to a longer measurement time for each frequency step.

In [9] a measurement campaign at 300 GHz with directive antennas in a small office environment is presented. For one setup with one transmitter and one receiver the azimuth plane is mechanically scanned in 2° steps to separate the individual transmission paths with the directive antennas. For each step the CTF is recorded with a bandwidth of 50 GHz. Due to the long measurement time, some few seconds per CTF and 90 h for one setup in total, dynamic scenarios with moving objects can obviously not be investigated. MIMO measurements can be simulated by conducting several measurements with varied transmitter and receiver positions. Otherwise MIMO measurements at 300 GHz are not feasible due to the limited number of ports.

Taking everything into account, very precise channel measurements can be achieved in static environments using a VNA. A minor limitation is the restriction to one waveguide band at a time. The most important drawback is that wideband measurements with moving objects or transmitters or receivers are impossible.

C. Correlation based measurements

In a correlative channel sounder a known pseudo random sequence $p_{tx}(t)$ is transmitted over the channel $h(t)$ resulting in the received signal $r(t)$.

$$r(t) = \int h(\zeta)\, p_{tx}(t-\zeta)\, d\zeta \tag{2}$$

At the receiver, the cross-correlation function of the received signal with the identical but delayed by τ and complex conjugated pseudo random sequence $p^*_{rx}(t-\tau)$ is calculated.

$$\begin{aligned} E\{r(t)\, p^*_{tx}(t-\tau)\} \\ &= E\left\{\int h(\zeta)\, p_{tx}(t-\zeta)\; p^*_{rx}(t-\tau)\, d\zeta\right\} \\ &= \int h(\zeta)\, P(\tau-\zeta)\, d\zeta \end{aligned} \tag{3}$$

If the autocorrelation function $P(\tau - \zeta)$ of the pseudo random sequence is the Dirac delta function the result is identical to the channel impulse response. Therefore, a good choice for the pseudo random sequence is an M-sequence because its autocorrelation function is a good approximation to the Dirac delta function. [10, 15]

In Fig. 2 a simplified setup of a channel sounder is depicted. The pseudo random sequence is mixed up into the frequency range of interest. Here, Eq. 3 is valid in the equivalent baseband. In order to correctly estimate the complex

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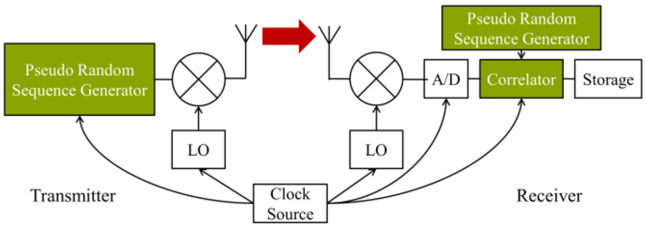

Fig. 3 Simplified schematic of a correlative channel sounder

channel impulse response in the baseband, receiver and transmitter need to be synchronized. For THz frequencies, one single clock source is used also to derive all the local oscillators (LO) with sufficient precision. The degree of fulfillment of the requirements is presented in the next chapter with a concrete example.

IV. Novel Correlation-based Channel Sounder for 300 GHz

The novel, recently acquired 300 GHz ultra-wideband channel sounder essentially works according to the scheme in Fig. 2. The technical parameters are summarized in Tab. 1 and explained in the following. The clock frequency of 9.22 GHz is used to generate the M-sequence and determines the duration of each chip. The bandwidth is approximately 8 GHz because most of the sequence power is concentrated within 8 GHz in the frequency domain. After filtering, the signal is mixed up (with the clock frequency) into the frequency range from 5 to 13 GHz, the second side band is suppressed by filtering. These steps are integrated in a so called "sensor node", c.f. Fig. 3. Each sensor node also comprises a receiver. Within the receiving branch, a quadrature demodulator is realized to record the received signal. Since high speed A/D converters are expensive and have a worse performance in terms of dynamic range and noise, a subsampling technique is used. Hence, with a fixed subsampling factor of 128 and the fixed 12th order M sequence the recording of one sequence (for one CIR) takes 56.9 µs (= 128·4095·1/9.22 GHz). The recordings can be saved on integrated SSDs using the full measurement speed. The cross-correlation is performed as offline processing afterwards. For "real-time" visualization and later evaluation (if a lower measurement rate is sufficient), the average of 64 sequences is always transmitted to the controlling laptop. Here, the cross-correlation is done in real-time. To achieve a carrier frequency of 304.2 GHz, wideband frequency extensions are connected to the sensor nodes, c.f. Fig 3. Antennas can be attached by a standard waveguide flange. The local oscillator for the extensions is again derived from the main clock. A central unit which is connected to each sensor node by network cables as well as RF cables distributes the main clock and provides the data transfer to and from the controlling laptop.

In Fig. 4 an example of a Channel Impulse Response (CIR), normalized to an overall power of 0 dB, is depicted. The duration is 444.14 ns (= 4095·1/9.22 GHz) and allows a maximum path length of approx. 133 m. The delay resolution is the chip duration of 108.5 ps which corresponds to a length of 3.25 cm. Of course the complex channel impulse response enables the determination of smaller differences in path lengths based on the phase information. A maximum of 17,590 CIR/s (= 1/[128·4095·1/9.22 GHz]) can be recorded. The inter-impulse response time is 56.9 us. The theoretically maximum Doppler frequency is consequently 8.8 kHz. According to Eq. 1, this is equivalent to a maximum speed of 31.7 km/h. In reality, this is lower but surely sufficient for walking persons and their swinging arms. At a first glance, the dynamic range can be estimated as 60 dB in Fig. 4. The dynamic range can be further increased by averaging channel impulse responses, thus in trade for a lower measurement rate.

Two more noteworthy details are included in Fig. 4. First, the delay of e.g. the direct path has to be calibrated to the "real" value according to the distance between transmitter and receiver. While the relative timing is correct, the absolute value is lost in the cyclic recording. Second, there are several strong impulses, especially the one at about 290 ns. Not all of these are additional propagation paths because of a too low attenuation for the additional delay. In fact they are caused by non-linear effects originating from the frequency extensions. In order to remove these, an offline calibration with a reference back-to-back measurement will be necessary and discussed together with the results of a measurement campaign. Thus, the CIR is shown without offline calibration here.

The main unit of the channel sounder supports up to eight sensor nodes simultaneously. Only four of those are equipped with integrated SSDs for real time recordings. In addition, two

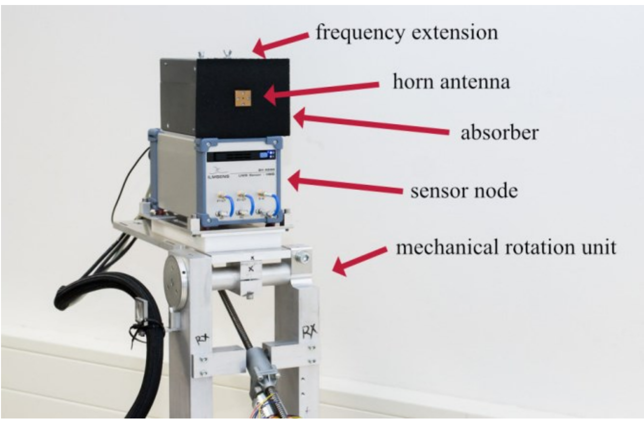

Fig. 4 Sensor node with frequency extension on a rotation unit.

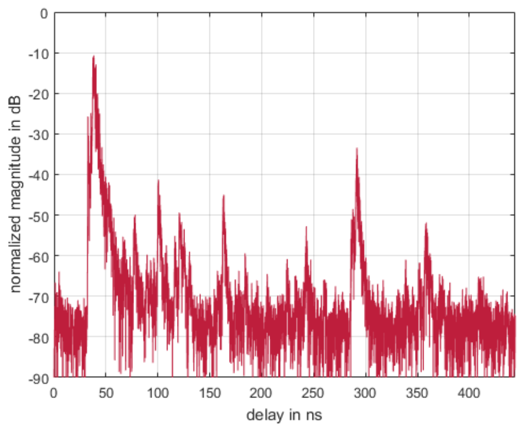

Fig. 2 Example of a channel impulse response with averaging.

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TABLE I. TECHNICAL PARAMETERS OF THE CHANNEL SOUNDER

Parameter	Value
Clock Frequency	9.22 GHz
Bandwidth	~ 8 GHz
Chip duration	108.5 ps
M-sequence order	12
Sequence length	4095
Sequence duration	444.14 ns
Subsampling factor	128
Acuisition time for one CIR	56.9 µs
Measurement Rate	17,590 CIR/s
Center Frequencies	9.2 / 64.3 / 304.2 GHz
SISO/MIMO	up to 4x4

frequency extensions for the receiver and two for the transmitter have been acquired for 300 GHz and 60 GHz, respectively. This way, MIMO measurements are supported up to 4x4 at UWB frequencies, 2x2 at 300 GHz and at 60 GHz. The transmitters are switched on and off in a configurable time-multiplex.

Comparing the technical parameters with the requirements from the applications, this channel sounder enables measurements in dynamic scenarios at 300 GHz for the first time. An even wider bandwidth would be beneficial but 8 GHz is absolutely sufficient for meaningful results. The channel sounder can easily be transported. Even in static environments with mechanical rotation units it provides for a significant speed up since the limitation now results from the rotation speed instead of the data acquisition. Only wireless front- and backhaul links cannot be measured with this device because the cable length between transmitter and receiver is limited to 20 m.

V. CONCLUSION AND OUTLOOK

The currently proposed and discussed applications for THz communications have been review. A focus was the derivation and compilation of meaningful technical requirements for propagation measurements. The strengths and weaknesses of the main techniques for channel measurements have been summarized and a novel 300 GHz ultra-wideband channel sounder has been presented. This channel sounder enables new significant measurements especially in dynamic scenarios in the future.

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